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Spacecraft Anomaly Attribution Tradecraft Must Evolve

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ABSTRACT

In response to the 2010 U.S. National Space Policy's call to "rapidly detect, warn, characterize, and attribute natural and man-made disturbances to space systems" the Spacecraft Anomalies and Failures (SCAF) Workshop has been pressing the community to improve skills in anomaly attribution. Five years of presentations, case studies, and insights have identified a clear requirement to create a spacecraft anomaly reporting standard. This new standard is motivated by the fact that previous anomaly investigations suffer from lack of diagnostics on spacecraft, limited benefit for operators to determine root cause, uncertainties in vulnerability models, and complicated space environment phenomena. As a result, it is important for this process to be both effective and efficient or else it will not be embraced. The Universal Satellite Anomalies Analysis Advisor, USA^3 is a proposed starting point for this solution: must assign anomaly/failure root cause to the (1) lowest possible hardware level associated with a (2) specific causative trigger by (3) tracking symptoms in time (both in relative and absolute terms). The ability to discern the cause of a space system failure will become more important as more new space users operate new satellite systems, the orbital debris hazard continues to grow, and space system performance becomes more ubiquitous to everyday life on Earth. This paper provides a starting point that through interagency and cross-community review and refinement may evolve into an anomaly attribution framework standard.

BACKGROUND

Spacecraft anomaly attribution (i.e., determination of root cause) is critical for a variety of reasons. The ability to determine the root cause of a satellite anomaly provides the means to (1) validate space environmental models; (2) give feedback to design and parts selection; (3) support vulnerability and failure model enhancements; (4) provide input for insurance processing; and (5) contribute insights into geo-political discussions about disruption of satellite operations.

At a higher level, we are striving to improve anomaly attribution because the U.S. National Space Policy 2010, Presidential Directive-4, calls for us to do so:

"Improve, develop, and demonstrate, in cooperation with relevant departments and agencies and commercial and foreign entities, the ability to rapidly detect, warn, characterize, and attribute natural and man-made disturbances to space systems of US interest."

As the space environment becomes more globalized and populated with first-time users, anomalies will likely continue to occur even as reliability of legacy space systems improve.

The determination of root cause for satellite anomalies (i.e., anomaly attribution) is complicated by (1) the dynamic space environment; (2) the lack of onboard diagnostics to aid in anomaly investigations; (3) the lack of motivation of space programs to determine root cause and share failures with others; (4) lack of spacecraft (system, subsystem, and component) design information; (5) inconsistency between the design and the final state a satellite was launched; (6) the complexity and variability of failure modes such as impacts, charging, contamination, etc.; (7) the fact that failures often are the result of more than one trigger; and (8) lack of common terminology and a standard anomaly attribution process.[1-7]

The net result of these investigations is that a new process for the investigation and documentation related to satellite anomaly attribution root cause is needed to enable the sharing of anomaly data community-wide to improve space operations assurance for all space systems. This new approach primarily focuses on solving the last of the eight issues outlined above understanding the importance of the context that the first seven issues provide.

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The original direction of the anomaly attribution process was to look back at previous anomalies and start to implement a new way of examining previous anomalies across a variety of sources to weave together a unified database of anomalies. To execute this approach, anomalies from the following sources were examined (1) Satellite News Digest: open source web site at https://www.sat-nd.com/; (2) LEO debris events compiled by D. McKnight (included in Appendix A); (3) NASA Goddard Space Flight Center database[5]; (4) NASA Spacecraft Anomalies Report[6]; (5) NASA SOARS/META database (only available through NASA); and (6) XL Catlin insurance anomalies.

The major components of the USA[3] format are: (1) name of anomaly; (2) Dates – event, documentation, and resolution; (3) Spacecraft Specifics – orbit, object characteristics, and state before/after event; (4) Symptoms 1, 2, and 3 (as appropriate); and (5) Attribution (i.e., root cause). This process has two major design objectives:

- Trace the event to the lowest possible component of the spacecraft (i.e., mission effect to system to subsystem to component) and;
- Recreate an accurate timeline of measurable and inferred events to insure that cause and effect hypotheses are tested sufficiently.

The lessons learned from this investigation resulted in the conclusion that past anomalies databases are not of sufficient common terminology and process to be leveraged by the USA[3] approach. Instead, a new guideline needs to be created that will enable future anomalies to be combined and global observations and insights made to assist all space users to minimize future failures.

ANOMALY ATTRIBUTION PROCESS

As a result, a new anomaly attribution process is proposed. There are many very robust and complete anomaly attribution processes already established.[8-10] These types of resources may well be referenced and used often during the execution of the framework described in this paper.

However, the goal of this process is to create a guideline that is concise, readable, and compelling. In order for this to be the case, it cannot be complete, like many of these other solutions. In addition, it must be community-agnostic (i.e., can be used equally well for large military spacecraft and small commercial platforms).

With that spirit in mind, there are a few key aspects that must exist within this "guideline" or "framework." These are (1) clear objective(s), (2) standard terminology, (3) overarching principles, and (4) standard process. These four components will now be presented in that order.

Clear Objectives

There are two objectives of the proposed anomaly attribution process: (1) provide guidelines to standardize the way spacecraft anomalies are described, recorded, and shared to enable future anomaly reports to be easily combined to provide insights to enhance space operations assurance for the entire community; and (2) assemble lessons learned and insights about spacecraft anomaly attribution that can help spacecraft operators better determine the root cause.

Objective 1 is largely satisfied by the following "Standard Terminology" section. The basis of applying best practices and disciplined anomaly investigation methods can only succeed if everyone is first using the same terms. This list of terms is an essential aspect of the development of this overall anomaly attribution guideline partially because it is so important and partially because it is a tedious task.

Objective 2 is largely satisfied by the remainder of the guidelines. It is important to note that this document is striving to provide a "lean" process. That is to say, it is comprehensive in topics but not overly prescriptive in how to satisfy the. There is an emphasis on suggesting to only do work that efficiently contributes to a solid root cause determination for an anomaly.

Standard Terminology

The framework of what terminology needs to be agreed upon begins with the definition of an anomaly: A spacecraft anomaly is defined as a functional perturbation to a satellite component, subsystem, or system that can be traced to a manmade or natural trigger. Even if the "anomaly" was expected, it is still an anomaly to the operations of that part of the satellite.

However, from the Orion programs[11] a different definition for anomaly and failure are proposed: An anomaly is defined as any deviation of system, subsystem, and/or hardware performance beyond previously established limits. A failure is defined as the inability of a system, subsystem, software/firmware, and/or hardware to perform its required function.

Part of the purpose of this paper is to motivate feedback; so, which definition of anomaly and failure do you prefer? Some early reviewers have suggested that only major permanent anomalies or failures will ever really be assessed using a comprehensive anomaly attribution process.

The "devil is in the details" no matter which anomaly definition is used. The listing below provides an initial framework for the terms that need to be considered to be included in this terminology section.

Spacecraft Mission - the ultimate purpose of the satellite:

- Remote sensing (or Earth observation)

- Meteorology

- Position, navigation, & timing (PNT)

- Communications (voice, video, and data)

- Science and astronomy

- Manned spaceflight

System - primary supporting function of space platform:

- Payload
- Communications (i.e., telemetry, tracking, and control)
- Data Handling
- Power
- Propulsion
- Attitude Determination & Control
- Thermal Control
- Structure

Subsystem - key segments of a system:

- Communications system has subsystems of antenna, transmitter, receiver, transponder (i.e., transmitter and receiver together), diplexer & switches, and signal processing.
- Data handling system has subsystems of command unit, clock, telemetry, recorder, memory, pulse modulation encoder, and fault protection.
- Power system has subsystems of batteries, fuel cells, power control unit, regulators/converters, wiring, and solar arrays.
- Propulsion has possible subsystems of thrusters, propellant, tank, fuel lines, pump, nozzle, etc.
- Attitude Determination & Control system has subsystems of control computer, reaction wheels, control moment gyros, magnetometer, Earth sensor, star sensor/tracker, sun sensor, horizon sensor, actuator/thruster, etc.
- Thermal control system has possible subsystems of louvers, MLI, heat sink, electric heater, etc.

Component - key subset of a subsystem that nominally serves a clear traceable purpose to a subsystem. Typical components of several subsystems are detailed below:

- Battery has components of casing, electrolyte, anode, and cathode.
- Star tracker has sensor, memory, processor (i.e., CPU), and power conditioning.
- Signal processing has pre-amplifier, timing/control (clock), power conditioning, and analog-to-digital converter.

Overarching Principles

Four key principles are proposed for development of an anomaly attribution procedure:

RESOLUTION: Assign the anomaly to the lowest hardware level possible. For example, component failure is more useful than system or subsystem degradation since there are so many possible components within a subsystem or system.

CAUSALITY: Identify the causative phenomena (i.e., trigger) uniquely. For example, rather than stating "space weather," determine between electron or proton flux or charged particles.

TIMELINE: Time sequencing is very important; build a timeline of when symptoms occurred. Note that this may not be when they were first detected or observed.

OPTIONS: Have you proposed three alternatives to the potential root cause before deciding on one to insure that you are not just trying to find data to support your first hypothesis (i.e., avoid confirmation bias).

These four principles are not created equal. The first three are engineering directives that drive information gathering in three different dimensions: (1) Resolution relates to hardware (i.e., what failed); (2) Causality focuses on a trigger (i.e., what caused failure); and (3) Timeline empowers cause and effect (i.e., order of events).

The last principle (i.e., develop three options before deciding on root cause) provides a guard against fixating on a root cause too soon (i.e., without considering dissenting options to the first viable option).

Standard Process

The process by which these principles can be applied to investigate an anomaly will occur after three planning steps detailed below:

Establish an Anomaly Attribution Team:

The makeup of the anomaly attribution team is critical to determining a root cause. The makeup and execution of this team should be planned for well before any event. This team should reflect a diversity of insights from across your organization and could initially include[12]:

- Program Manager (PM) for space platform that was affected: responsible for the space system's performance.

- Boss of PM for space platform that failed: show management commitment to importance of anomaly attribution process.
- Primary space system operator for platform affected: knowledgeable of operational performance but not an engineer with knowledge of design; knows "function over form."

- Payload system lead for space platform affected: payload is reason for all of the other systems so he/she represents platform "customer."

- Power system lead for space platform affected: power system is integral to any anomaly so all other systems are sensitive to its performance.

- Attitude and control system (ACS) lead for space platform affected: ACS is integral to any anomaly especially when one of the symptoms is an orientation perturbation.

- Communication system lead for space platform affected: communication system is integral to any anomaly as cessation of communications may be the first indicator of some anomalies.

- Thermal management system lead for space platform affected: thermal management system may be integral to some anomalies as temperature variations from normal may be both an intermediate indicator of an anomaly or the primary mission effect.

- System engineer from a different space platform than affected: objective, but qualified, technical bystander.

- Manager from a different space platform than affected: objective but qualified management bystander to lead the investigation.

As the investigation progresses, some of the anomaly attribution team representatives (e.g., thermal management, etc.) may be dropped off of the team and others could be added.

Retrieve System Documentation:

The likely first step of an Anomaly Attribution Team is to retrieve space system documentation. Information about the space system that has suffered an anomaly may actually be very difficult to access.

Just because you are operating a satellite does not mean that you actually know what the thickness of propellant tanks are or the number of layers of MLI or spacing between the MLI layers of them around a battery casing.

While it may never be needed, it is prudent to start an operational space program with a complete set of documentation for the satellite you are operating. A good test of completeness of the documentation is whether it is sufficient to allow you to build a new one from the specifications.

This baselining of system documentation is essential since once an anomaly occurs and you are trying to recreate a failure or test phenomenological issues, differences in what has been deployed to space cannot differ from your modeled understanding of it if you hope to determine root cause.

Assemble Anomaly Information:

The source and types of data needed depend significantly on the characteristics of the satellite and its operations. Knowing where you might find useful anomaly information is critical. It may come from on-board diagnostics (e.g., telemetry from temperature sensors), mission performance (e.g., data being transmitted by system only at half of normal data rate), third-party observers (e.g., astronomical observers sensing a tumble of your, previously 3-axis stabilized, satellite), etc.

It is critical that data not be filtered too soon as to what is relevant and what is not. Oftentimes, the leading candidate for the root cause might skew the investigation by causing the investigators to preferentially pay attention to data that confirms the first likely root cause candidate. Guard against this tendency to limit data assemblage too soon and based upon being "irrelevant" to initial theories for the anomaly root cause.

The actual execution of the four principles is largely done in support of the analysis. The needed activities are largely captured by model runs, simulations, and testing.

Model Runs, Simulations, and Testing:

The process by which a root cause is determined is highly iterative and includes information gathering, reporting, model runs, simulations, and testing in order to adjudicate hypotheses; in essence, determine the one best hypothesis. However, explaining alternative hypotheses that have eventually been ruled out provides reviewers both results and the logic to derive these results.

It is also important to remember that oftentimes an anomaly is the result of more than one trigger acting over a period of time. When a minor failure (that produces no immediate mission effect) is coupled with a loss of redundancy to create an anomaly, the trigger for the second event (e.g., loss of redundancy) may be judged (erroneously) as the sole contributor to the reported anomaly (i.e., mission effect).

Figure 1 displays the total anomaly attribution process:

- Planning steps are critical to the overall sequence and eventual anomaly resolution;

- Execution applies engineering and cognitive principles to efficiently investigate an anomaly; and

- Model runs, simulations, and testing provide the concrete attribution information. Appendix C contains a comprehensive list of root cause attribution techniques taken from Reference 10.

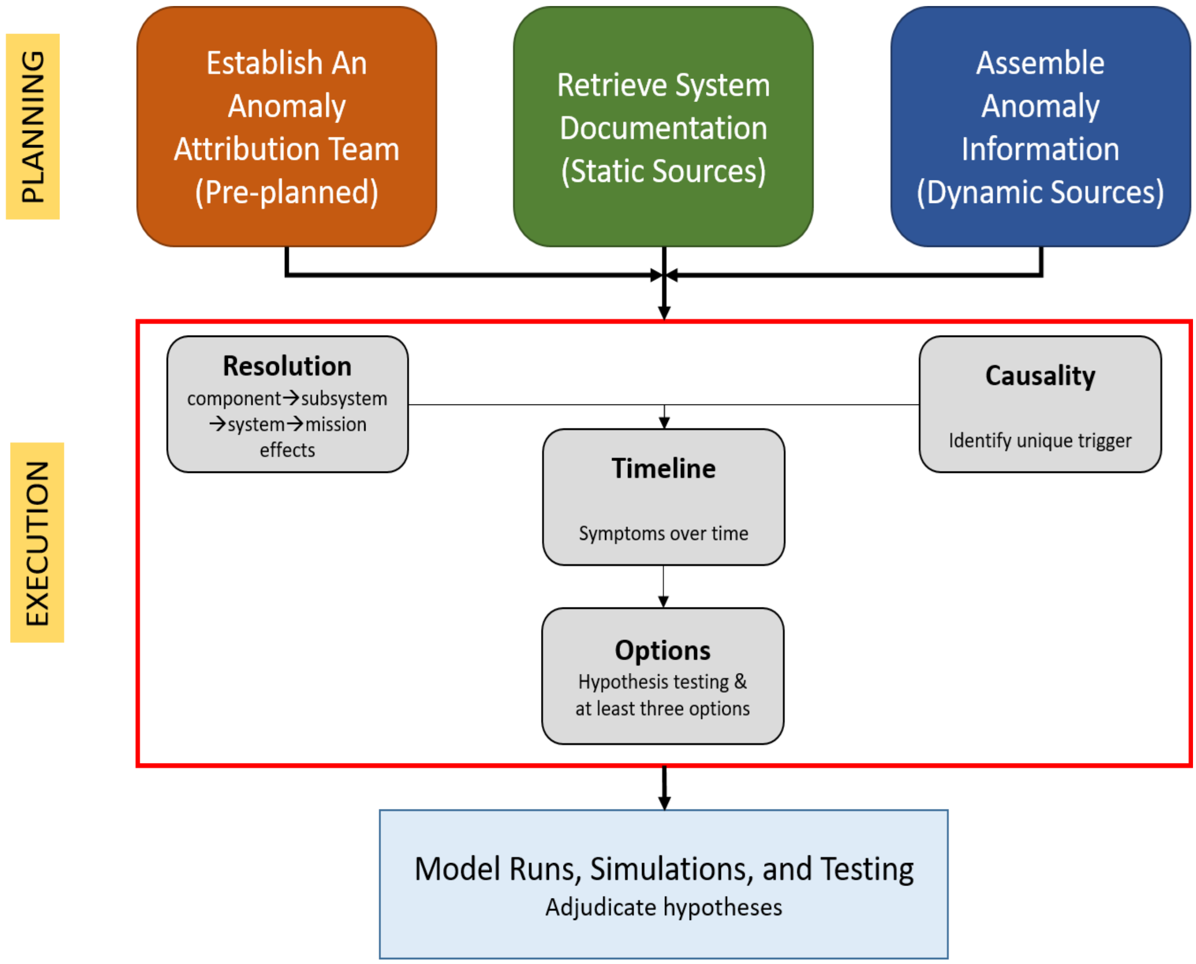

Figure 1. Anomaly attribution process includes both planning before an event and execution of key principles afterwards.

SUMMARY AND CONCLUSIONS

As this process is in its infancy, the hoped-for status over the next year is to present this proposed process to as many people as possible with a focus on people with operational space experience.

The goal is to be useful but not onerous so that everyone will be willing and excited about reading the guideline and can then incorporate relevant aspects of the process into their existing operational procedures.

It should be noted that no matter how much we focus on the engineering and technical aspects of the anomaly attribution process, we cannot forget that the administrative aspects of this sequence are just as important; if overlooked, the entire process will fail.

A parting observation on the difficulty of this process can be made when looking at how to discern if a spacecraft has been struck by a piece of nontrackable space debris. The ability to sense whether or not a satellite was disrupted by an orbital debris impact is not as easy as it might seem.

The likely debris impactor to on operational satellite in LEO will be a smaller fragment, since there are more of them: there are over 500,000 fragments in LEO larger than 5mm-1cm versus 18,000 cataloged objects). Anomalies or failures from a debris impact will likely be a fast-acting effect (i.e., not a slow, steady reduction in performance).

However, having a rapid reduction in solar power that might be attributed to a debris particle destroying a portion of a solar array may look identical to a reduction in power due to short in a solar array due to a charging event.

The sequence of parameters that may not be known well enough to confidently attribute a cause of an anomaly as a debris are summarized in Figure 2.

A test that has become more suggestive of a debris impact is summarized in the table of impact indicators provided in Appendix B. However, it is a straightforward requirement (though problematic in reality) that a debris impact can really only be verified by visual inspection or by having two independent, related observables occur simultaneously. For example, if the solar array power output drops by 20% instantly while an angular perturbation is detected for the entire spacecraft then particulate impact is likely to be the root cause.

Similar tables to the one included in Appendix B for indicators of a debris impact but for other anomaly triggers would provide a valuable resource for future anomaly investigations. These would include electrostatic charging, total radiation dose, displacement damage, single event upset, contamination, and atomic oxygen erosion, at a minimum.

Acknowledgments

The evolution of the Spacecraft Anomalies and Failures (SCAF) Workshops over the last five years from scientific discussions to operational dialogues highlights the maturation of this community.

The SCAF Workshops have been supported by many people in government, academia, and industry. However, the following people have invested significant “sweat equity” into making this sequence of techno-policy workshops to be a great success: Jeff Blackman, IAI; Chris Kunstadter, XL Catlin; Mark Matney, NASA/ODPO; Jonny Pellish, NASA/GSFC; Jesse Leitner, NASA/GSFC; and Susan Hastings, The Aerospace Corporation.

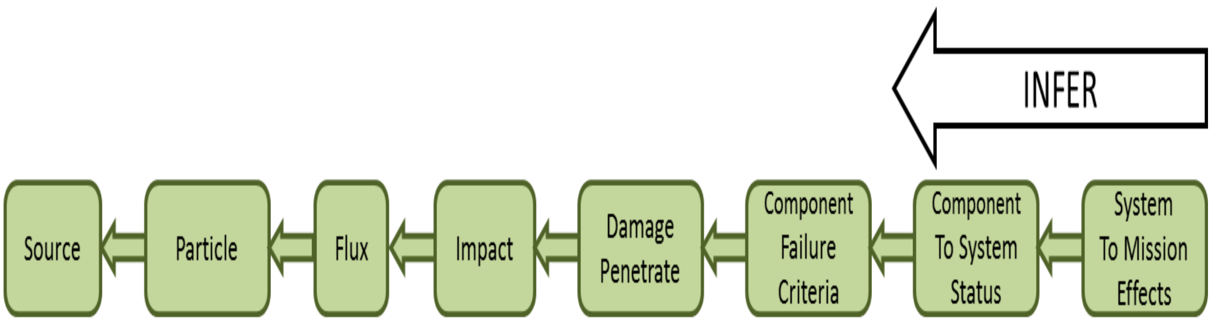

Figure 2. The ambiguity of translating a change in mission performance to an impact, flux, particle, or even, eventually, a source requires a significant amount of information that is often not known.[13]

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12. As an exemplar for a successful anomaly attribution team, the European Space Agency’s team used to quickly and effectively determine the root cause of the Sentinel-1A anomaly in 2017 included a spacecraft flight control expert, the control team manager, the mission manager, a flight dynamics expert, a debris expert, and support from the manufacturer of the solar array. (Source: Holger Krag, OPS-GR, ESA/ESOC)
13. "Evaluation of MMOD Risk Predictions with Available On-orbit Assets", NASA Engineering and Safety Center Technical Assessment Report, March 2017.

Appendix A. LEO Potential Particulate Impact Events

Event	Object(s)	Size/Mass	Altitude (km) & Inclination	Anomaly Date & Time	Lat/Long
Cosmos 1934 struck by debris	Russian P/L (18985) 1988-023A	P/L: ~2-4m^2 700-800kg?	950 x 1010 i=83	12/23/91 @980km @14.3km/s	~50N/ Unknown
	debris #13475	Debris:~0.6kg			
Cerise boom severed	French Recon Sat (23606/1995-33B)	~0.49 m^2 50kg	656 x 681 i=98.1	07/24/1996 0948; On ascending pass; impact velocity of 14.8km/s @685km	38.2S/59.7E
	Debris fragment (18208)	~0.098 m^2 ~1-4.5kg?	653 x 685 i=98.5		
SUNSAT (SO-35)	South African university small sat	64kg; 45/45/60cm	400 x 838km; i = 93°	01/19/2001	Unknown
JASON1	NASA/CNES Oceanographic sat, 2001-55A; 26997	Bus 1m cube with 4m long solar arrays; 500kg	~1336km and 66°	03/2002	10.75S; 59.18E
Cosmos 539	Russian geodetic satellite (6319) 1972-102A	6m^2,600kg;2m cyl + solar arrays	1340 x 1380km i=74	04/21/2002	72S/36.75W
DMSP-5B F5 R/B hit by CZ-4 debris	Thor Burner 2A LV (07219) /1974-15A	1m^2 37.5-50kg	775 x 885 i=99.1	1/17/05 0214; impact velocity of 5.7km/s	80.6S/53W
	Chinese R/B frag (26207)	0.06m^2 ~1-2kg	671 x 847 i=98.2		
Nadezhda 2 R/B	R/B	Cyl; D=2.4m x L=6m	950x1015km; i=83	06/22/2005	Unknown
JASON1	NASA/CNES Oceanographic sat, 2001-55A; 26997	Bus 1m cube with 4m long solar arrays; 500kg	~1336km and 66°	09/2005	52.36S; 100.4E
Cosmos 2251 / Iridium 33 collision	Russian Comm. Sat. (22675)	~6m^2 ; 900kg	778 x 803km; i=74	02/10/09 1656 @ 789km @11.6km/s	72N/97E
	Comm. Sat. (24946)	>2.6m^2 560kg	785 x 794km i =86.4		
Iridium	SV29	>2.6m^2 560kg		05/24/2009	???
EOS-Terra	A-Train satellite NASA	6.8m long, 3.5m wide; 5,190kg	705km; i=98.2°	10/13/2009 1624GMT	???
Aura	NASA atmospheric science satellite	1,765kg; 6.9mx2m body plus 18m array	685 x685; i =98.2°	03/12/2010	Unknown
BLITS altitude drop	Laser ranging target (35871)	~0.023 m^2 7.53 kg	832 x ~800; i=98.6	0800 on 01/22/2013	80.6S/53W 69.4N/38.9E

Event	Object(s)	Size/Mass	Altitude (km) & Inclination	Anomaly Date & Time	Lat/Long
Pegaso unresponsive	Ecuadorian cubesat (39151)	~0.075m^2 1.2 kg	650 x 654; i=98.1	05/22/2013 0538	62.98S/ 90.48W
Iridium-47	Comm sat 1997-082C SATNO 25106	>2.6m^2 560kg	785 x 795km i = 86.4°	06/07/2014 0330 UTC	Unknown - checking
Iridium-91	Comm sat #27372	>2.6m^2 560kg	785 x 795km i = 86.4°	11/30/2014 1615UTC	Unknown - checking
WorldView-2	Payload #35946	4.3mx2.5m; 7.1m solar arrays; 2800kg	770km i= 98.54°	07/19/16 (5:09pm EST)	Unknown - checking
Sentinel-1A	Payload #39634	3.4m ×1.3 m bus; 2,170kg	693km sun-synch; i=98.18°	08/23/16 17:07:37UTC	
Delta R/B	Rocket Body 1968-114B	6m x 1.4m; 800kg	1,450km 101.35°	Unclear	Unclear

Appendix B. Debris Impact Indicators

Observable	Name	Physical Relevance	Exemptions	Examples (See Appendix A for list of MMOD anomalies)
Abrupt loss of power in tandem with an angular perturbation to a satellite is indicative of a particulate impact of a solar array. Sometimes the perturbation occurs without a drop in power in case it strikes a joint or edge of the solar array.	Ghost "Power" Torque	The farther out the impact occurs on the array and the more massive the impacting object is, the greater the angular perturbation will be. More massive objects impart a smaller percentage of their original momentum to the solar array than smaller (marginally or non-penetrating objects).	For micrometeoroids, they have a tendency to vaporize on impact, which does not transfer mechanical momentum as well, however, the ejecta is released in the opposite direction to the impact direction that may produce a momentum enhancement effect (due to the rebounding ejecta from the impacted surface).	GOES-13 (2013) angular perturbation was determined to have been from a micrometeoroid strike since it occurred during a helion micrometeoroid event and examination of the "rush hours" for GOES-13 did not hint at an orbital debris impact.
Short in exposed cabling, degradation of thermal control, or start of a leak of propulsion system in tandem with an angular and/or linear perturbation to the spacecraft.	Hybrid Combination Failure	These subsystems are closer to the center of mass of the satellite so impacts on them are not as likely to cause an angular perturbation. A linear impulse will change the orbit rather than the orientation of the satellite.	It is difficult to tell the difference between a micrometeoroid or orbital debris impact except that micrometeoroid impacts often create electrical anomalies (due to their very high velocities) in addition to the physical damage. An impact-induced electromagnetic pulse (EMP) looks similar to electrostatic discharge (ESD) except that it might correlate with a peak in a meteor shower and be counter to normal ESD triggers (i.e., decreasing solar activity and coming out of eclipse).	Olympus (1993), ADEOS-II (2003), and ALOS (2011)

Abrupt change in an object's orbit despite there being no energy source onboard to provide such a perturbation and no debris liberated. This is more likely in GEO because of the lower impact velocities.	Ghost Impulse	A piece of nontrackable debris that strikes an object may only cause a change in the orbit without producing any debris.	Meteoroids are not massive enough for this to typically occur and a debris impact in LEO is likely to create debris but not so in GEO where momentum might be absorbed fully.	GOES-10 (2011), derelict payload in GEO graveyard, had its orbit altered abruptly (dropped 20km) but no debris liberated. The perturbation was much greater than could have been expected from an ESD event or SRP.[1]
Abrupt change in an object's orbit despite there being no energy source onboard to provide such a perturbation but debris is liberated	Impulse and Debris	This is difficult to differentiate from an explosion of a subsystem for an operational spacecraft (since there are sources for energy liberation such as battery casing ruptures or propulsion system malfunctions).	This is more likely to occur in LEO with the greater closing velocities for orbital debris than in GEO. However, micrometeoroid impacts will be difficult to differentiate from strikes from nontrackable orbital debris but also are less likely to have sufficient linear momentum transferred.	Cosmos 1934 (1991), DMSP rocket body (2005), and BLITS (2013). The 1991 C1934 event was not discovered until archives were searched after the 2005 DMSP rocket body glancing blow occurred.
If two LEO cataloged objects collide, the result is usually at least the perturbation of one object and potentially the replacement of one object with a debris cloud. If both objects are large enough there will be two debris clouds.	Cataloged Collision	Hypervelocity impacts cause the solid material to behave as a liquid creating many more fragments and liberating them in all directions (relative to center of mass of fragmented object).	This is much more likely to occur in LEO with the greater closing velocities. At GEO, two cataloged objects colliding may not create as much trackable debris since it will be a much slower impact velocity.	Cerise (1996) and Iridium/Cosmos2251 (2009). Cerise continued to function, though below normal performance levels, for years after the encounter.
In LEO, if the event occurs near the object's apex (i.e., near its highest northerly or highest southerly latitude) it is likely an orbital debris collision.	Apex Trend	Collision hazard for a typical (i.e., high inclination object, i > 50°) LEO satellite is lower near equator and higher near apex.	This holds only for LEO high inclination (i > 50°) objects.	Of the five known encounters between trackable debris, four have occurred above 70° N or S; Cosmos 539, Cosmos 1934, Iridium-33, and DMSP R/B. Cerise occurred at 38°S.

In GEO, if the anomaly occurred during a "rush hour," then it is indicative of a debris impact.	Rush Hour Trend	The timing of debris impacts on a station-kept GEO satellite from derelict objects or debris will occur in regular intervals called "rush hours."	Not all debris syncs up with the "conga line" motion: 6-8 tracked objects (out of nearly 800) at any time have been seen to move counter to this motion. High area-to-mass objects may be perturbed by SRP and, therefore, present a collision hazard out of the "rush hours." These objects would, however, likely spend very little time in the vicinity of GSO assets so the collision probability is very low.	No examples
An anomaly that is temporary and/or is repeated is not likely to be debris-induced.	Multiple (Separate), Temporary	Impacts are rare events so it is exceedingly unlikely to have multiple on same satellite…	…unless it is close to a recently produced cloud (e.g., below a sloughing object or conjuncting a debris cloud from a recent breakup). If a particle impacts a non-critical surface, there may be a temporary pointing anomaly that may be correctable (i.e., temporary).	No examples
Multiple systems fail simultaneously while power is still intact yet no debris is produced.	Multiple Simultaneous	Assumed the only way for this to happen is for a fragment to knock out several systems at once. It would seem that debris would likely be produced from such an event.	If all systems are controlled by the same satellite central processor, failure of this component due to deep internal charging or disruption by a high energy particle could spoof this failure mode.	SUNSAT-35 (2001) claimed this failure mode, but no debris was observed.

Appendix C. Root cause attribution (RCA) techniques pros and cons.[10]

RCA Method	Pros	Cons
Brainstorming	Good technique for identifying potential causes and contributing factors.	Is a data gathering technique, not a classification and prioritization process.
Cause and Effect Diagram (Fishbone)	Permits consideration of many different items. Enables planning, executing, and recording results for multiple investigative paths in parallel.	Inability to easily identify and communicate potential inter-relationship between multiple items. Best suited for simple problems with independent causes.
Fault Tree Analysis (FTA)	Help to understand logic leading to event. Many software tools are available.	Requires knowledge of the process. FTA typically used as trial and error method in conjunction with a parts list.
Advanced Cause and Effect (ACEA)	Good tool for complex problems with dependent causes.	Requires thorough understanding of cause and effect relationships and their interactions.
Cause Mapping	Can be large or small depending on complexity of scenario. Allows for clear association between causes and corrective actions, with a higher likelihood of implementation.	Difficult to learn and use.
Why-Why Charts	A good tool for simple problems with dependent causes.	Typically, based on attribute-based thinking rather than a process perspective.
Process Classification Cause and Effect (CE) Diagram	Easy to construct and allow the team to remain engaged in the brainstorming activity as the focus moves from one process to the next. Invite team to consider conditions and events between the process steps that could potentially be a primary cause of the problem.	Similar potential causes may repeatedly appear at the different process steps.